AEROSPACE TECHNOLOGY INSTITUTE

Hydrogen Capability Network

Cryogenic Hydrogen Future Test Infrastructure and Supply Landscape

July 2025

About

This report is authored by the Hydrogen Capability Network with input from stakeholders engaged through a series of workshops, surveys and one to one discussions.

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About the Aerospace Technology Institute

The **Aerospace Technology Institute (ATI)** is an independent organisation that works alongside government and industry to transform UK aerospace through technology and innovation. The ATI is funded equally by the **Department for Business and Trade (DBT)** and by industrial recipients of project grants who pay a small levy. ATI projects are chosen and overseen through close collaboration with Innovate UK and DBT.

As well as running this portfolio of R&T projects, the ATI conducts strategic research projects to help define and answer systemic questions of value to the UK aerospace sector. In 2022 the ATI published the findings of the **FlyZero** project, which concluded that liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft.

The ATI Programme has made several investments in liquid hydrogen technologies to support the next generation of zero-carbon aircraft. The **Hydrogen Capability Network (HCN)** was launched in April 2023 funded by the Department for Business and Trade, to progress key recommendations from FlyZero which will enable the aerospace sector to deliver liquid hydrogen research and development (R&D).

Disclaimer

The report is based on input from the survey, collaborative workshop and wider ATI sector engagement and research up until April 2025. Although every effort has been made to ensure it reflects a comprehensive view of the UK landscape there may be capability that was not shared or available to be put in the public domain. The ATI does not accept liability for any errors, omissions or misleading statements and no warranty is given or responsibility accepted for any actions users may take based on the content of the report. The ATI reserves the right at any time to make changes to the material, or discontinue the report, without notice.

Cryogenic Hydrogen Test Facilities Summary

The HCN has found that the lack of available liquid hydrogen (LH2) test facilities and limited supply of LH2 at a reasonable price present a major barrier to advancing zero carbon aerospace technologies in the UK. The limited ability to test with LH2 has stalled the UK's development of fundamental knowledge and skills. These findings reinforce the recommendation that was made in the ATI's FlyZero project:

> "To address the UK's limited hydrogen-related skills and testing capabilities, **a cross-sector hydrogen technology centre** with open access facilities should be created to facilitate research into fundamental hydrogen behaviour (including cryogenics), requirements for safe handling, standards and regulations, material properties and test specifications. **It should act as a centre of excellence and provide an anchor for industry in the UK**." *FlyZero Executive Summary*

To determine whether the recommendation was still valid and understand the barriers in more detail the HCN engaged with stakeholders across the aerospace sector, LH2 test facility providers and hydrogen liquid and gas suppliers, through surveys, workshops and stakeholder discussions. This report captures the output from these engagements alongside the HCN's wider research.

Key Findings and Recommendations:

Test Infrastructure Demand

- Commitment for long term demand is difficult due to the uncertainty of technology development and test campaigns.
- Over the next two to three years most of the demand remains for small quantities of LH2, in the order of 1kg to 30kg/day.
- High cost is a barrier to entry for testing while lack of fundamental data and validated models increases the testing burden.
- Investment in diverse test facilities is necessary to support various stages of LH2 technology development. The infrastructure must evolve to meet the changing needs of the sector over time, from small-scale academic, material coupon and functional test of components to system endurance testing, supporting certification needs.

Test Infrastructure Provision and Liquid Hydrogen Supply

The UK's current and planned facilities provide a sufficient volume of LH2 to meet the sector's demand until the end of the decade. However, these facilities need to meet user testing requirements in terms of scale, functionality and access.

- **Facilities** – there are limited permanent LH2 test facilities in the UK, and little set up to cater for small-scale fundamental research. As a result, many universities are proposing to develop their own LH2 test facilities, with onsite liquefaction. Funding is being requested to build these and there is a risk of duplication.
- **LH2 Supply** – There is no supply solution for infrequent small volume demand, the only solution is a LH2 tanker of minimum order quantity (typically 2,500kg) costing from £50,000 upwards requiring quick use or suitable storage. Therefore, sites are turning to onsite liquefaction which has known inefficiencies and unreliability issues if liquefaction equipment is not used consistently.

- Due to uncertain testing demand and limited guaranteed offtake, making a commercial case for facilities is difficult. They are expensive to build, requiring liquefaction or insulated storage, limited guidance and lengthy approval processes.

Safety, Regulations, Standards and Guidance

Enhanced safety protocols and regulatory frameworks are vital to de-risk the adoption of LH2 technologies. Learning from testing at current facilities should shape the development of improved regulations and standards.

- **Regulations:** There is limited guidance to applying the full suite of regulations to liquid hydrogen facilities and no unified agreement on which standards and guidelines for safe operation, handling and testing with LH2 should be used. Consequently, organisations are interpreting multiple standards and guidelines in an attempt to manage the hazards for their sites. This has also made it difficult for insurance companies to assess risk, either declining requests or increasing premiums.
- **Standardisation:** Developing standardised physical interfaces to allow for a more integrated supply chain and deliveries from a range of gas suppliers to a single facility and establishing training standards and qualifications for test facility operators.
- **Standards and guidelines** – Encouraging collaboration to harmonise the most appropriate sections of standards to ensure that industry works to a common set of safe working practices and encourages open access to these guidelines. Until clear guidance and standards are implemented, a dedicated regulatory point of contact to advise the community should be appointed.

Collaboration, Coordination and Dissemination

Continued work to convene the sector is important to:

- Ensure safety and build a safety focused culture.
- Build expertise and knowledge, share learnings, guidance and data through a community of practice / forum.
- Build a consolidated demand picture for LH2 across the whole of the UK to make the business case for LH2 facilities and UK production more robust.

Long Term Strategy and Funding

A clear long-term strategy and sustained funding are essential to support the growth of the UK's LH2 sector. Given that there is more R&D needed to give confidence to progress to larger offtake agreements, this especially true while there is uncertainty in the demand curve. Early-stage funding is particularly important to reduce uncertainty and encourage investment as reducing the cost of testing will help industry and academia scale - this needs support from both government and industry.

There is a need to continue to monitor and improve the total demand curve and offtake agreements to help suppliers and facilities develop business cases based on the whole of the UK's requirements. There is a need for a facilities strategy to reduce duplication.

Finally, incorporating demand from outside aerospace, including marine, energy and transport in addition to gaseous hydrogen users, will add to the business case for LH2 supply.

Key points

- A robust and resilient LH2 supply network is essential. This includes exploring and supporting all viable domestic supply options, promoting collaboration among end users, and encouraging joint efforts with LH2 suppliers to improve cost-effectiveness of UK small-scale supply alongside a long-term UK supply solution.
- Given the cost of facilities, the difficulty in LH2 supply, the shortage of expertise and guidelines and the imperative to maintain safety, there should be a focus on fewer and more capable facilities.
- There should be an ethos of taking the testing to the liquid hydrogen, a centralised testing environment for fundamental research to promote collaboration and skills development.

In summary, the combination of the need to develop low TRL technology with a fluid that is not easy to simulate and very expensive to test in an industry where the end product is safety critical, is holding back the progress of technology development. Investing now in skills, equipment, and infrastructure is essential to support advanced testing and UK competitiveness in hydrogen technologies. There is evidence of other countries subsidising these early phases and it is essential to the UK economy these interventions are enacted to accelerate development and encourage private investment.

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1. Introduction

The Aerospace Technology Institute's (ATI) FlyZero project concluded that liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft. The FlyZero project identified a gap in the UK's liquid hydrogen capability. At the same time, the ATI published the UK aerospace technology strategy, Destination Zero, which identified that the UK could grow its market, as aircraft fleets transition to a new generation of ultra-efficient aircraft and begin to introduce zero-carbon emission aircraft. UK Government's *Advanced Manufacturing Sector Plan* targets an increase in the UK's share of the global market by value from 10% in 2025 to 15% in 2050.

While technology development timelines are not yet certain, achieving this market share is contingent on continued investment in technology development, regulation, and infrastructure across the ATI roadmaps.

In 2023 the ATI set up the Hydrogen Capability Network (HCN) which set out to make recommendations on strategic interventions for what is required to maximise UK industry competitiveness in the emerging liquid hydrogen-powered flight market. During the project, the team has connected with over 1000 stakeholders from across the UK. This included face-to-face discussions and site visits, and over 100 attendees from 44 unique organisations to the HCN's testing, research, and skills workshops. The HCN also ran a Cryogenic Hydrogen Research Conference in January 2025, with over 150 attendees from academia and industry.

Scope and methodology

To determine the liquid hydrogen (LH2) testing landscape, the HCN has engaged with current and potential test infrastructure providers, LH2 suppliers, and potential test users (from academia and the aerospace supply chain through to aerospace primes). This report sets out the view of current capability, planned capability and potential requirements and demand for different types of tests at different scales. It discusses the challenges associated with testing and operating test infrastructure with LH2 including the supply of the liquid hydrogen itself. The HCN has previously published a joint report on the *UK Cryogenic & Hydrogen Materials Testing Landscape*, which summarises the testing capabilities across UK for the evaluation of mechanical, thermal, hydrogen transport and other properties typically used to understand materials behaviour for design and certification purposes.

The HCN launched a survey in 2023 to understand the volume demand of LH2 over the coming decade. This was followed up by a survey in 2025 to refine detailed testing requirements for this demand, understand options for supply, and build a capability map of current and planned UK based facilities. This survey was supplemented with a test infrastructure and supply workshop which took place in March 2025 and was attended by 45 experts from aerospace, test infrastructure, hydrogen suppliers and academia. The goal was to identify what kinds of test and demonstration facilities are most urgently needed to build confidence in LH2 technology. The data captured in both surveys, and the knowledge discussed in the workshop and in separate stakeholder discussions has informed the findings and conclusions of this report.

Figure 1 shows a simplified view of the aerospace structural test pyramid and highlights the varying scale of tests which are required to certify a component or system. At the smallest scale, material coupons are tested in cryogenic conditions to build a fundamental understanding of mechanical and thermal properties. Testing then grows in scale to small elements using small amounts of cryogenic fluids. Test scale increases as the size of the component grows and different types of tests are required. Some components such as cryogenic pumps will require endurance testing and this requires large amounts of LH2 to be cycled through the component.

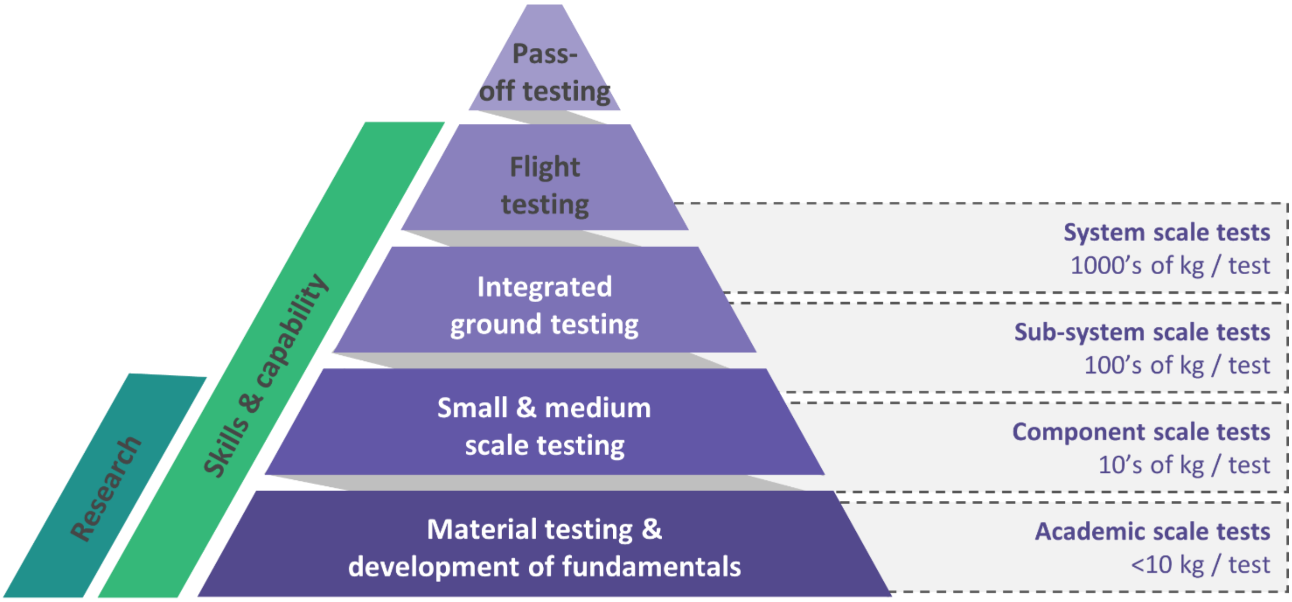

FIGURE 1: A SIMPLIFIED VIEW OF THE AEROSPACE STRUCTURAL TEST PYRAMID AND THE SCALE OF REQUIRED LH2

2. Challenges for Liquid Hydrogen Testing

There are several challenges and barriers that need to be considered in the planning and development of LH2 test facilities for safe operation. Many of these reflect the relative immaturity and early stage of the journey for potential adoption of LH2 as a fuel for achieving zero-carbon emission flight. There is a lack of data and fundamental understanding of LH2, guidelines for safe set-up and operation and skilled personnel.

Consensus from HCN engagement with the sector is that the development of LH2 technologies is relatively unique compared to the normal R&D cycle in the aerospace sector. The need to advance to Net Zero at pace means there is concurrent work planned across the early and mid -technology readiness levels (TRLs) in a field where there is insufficient test infrastructure, gaps in knowledge and a short supply of test guidance. Figure 2 shows the number of organisations planning testing across the TRL scales over the next five years.

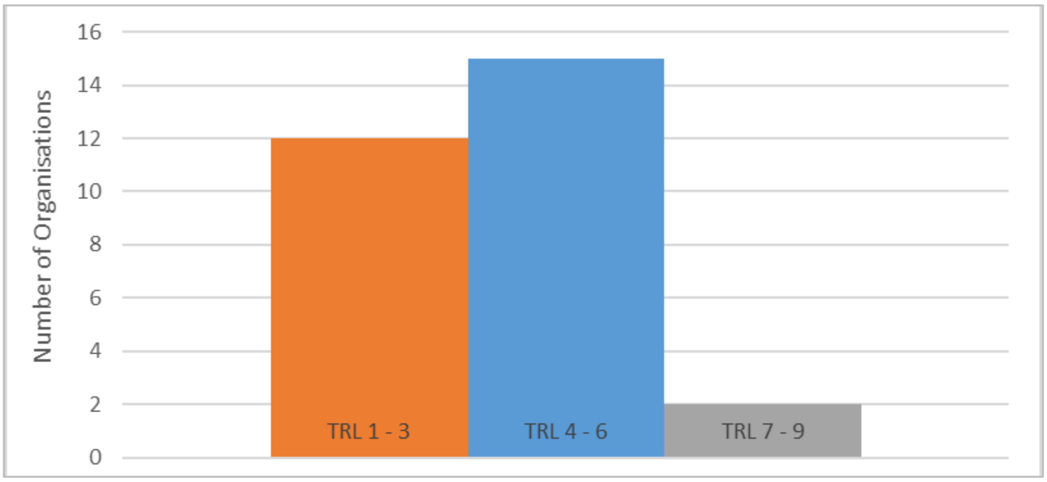

FIGURE 2 – NUMBER OF ORGANISATIONS PLANNING LH2 TESTING ACROSS THE TRL SCALE

The challenges can be considered from the perspective of the **test infrastructure users** undertaking the research and technology development, and the **test infrastructure providers** who have or are seeking funding to provide facilities, some of which are also users.

- **Test infrastructure users**: the lack of test infrastructure currently available in the UK, especially at small-scale at an affordable price; access to skilled personnel for test design and operation; and a lack of experimental data and standards.
- **Test infrastructure providers**: making the commercial case for investment due to uncertain user demand; capital cost of equipment; an uncertain and lengthy approvals process with lack of standards and guidelines.

Innovation and development of novel technologies requires a 'fail fast' approach to discover which technology works. It is essential to perform small-scale prototype testing of the low TRL technology before committing to investment to scale up. The challenge is made more difficult in that even small-scale testing is relatively expensive, due to the cost of the facility infrastructure and the LH2 needed.

2.1. Lack of Fundamental Knowledge and Experimental Data

As highlighted in the HCN report *Cryogenic Hydrogen Fundamental Research Summary for UK Aerospace* and the supporting detailed reports on the global landscape, there is a lack of fundamental understanding and experimental data, standardised test methods, health and safety guidelines and open access test facilities.

Experimental data and standardised test methods are required to validate numerical methods which are then used for design iterations and the reduction of future physical testing. However, the detailed understanding of the thermofluid behaviour of LH2 required for accurate simulations is insufficient and therefore LH2 simulations, digital tools and models remain immature.

As the development of this fundamental research, experimental data and test methods is happening concurrently with the technology development, there is likely to be more testing required with inevitable duplication in the testing undertaken. Some of which will need to be repeated at the point of certification when standardised test methods are available.

2.2. Cost of LH2 Testing

The costs of physical testing with LH2 is significantly more expensive than working with traditional aerospace fuels. This is driven by several factors such as the:

- volume of demand for facilities is still low or uncertain
- cost of capital outlay for facilities and equipment.
- cost of LH2 and associated specialised storage facilities.
- properties of LH2 (the need to chill-down equipment and reduce losses through boil off,).
- lack of standards, guidelines and best practice for safe design and operation of testing facilities, potentially resulting in high effort to design from first principles and ‘over engineering’ solutions to manage risks.

The cost of testing is similar to the cost of wind tunnel testing and in some cases more so; traditionally the industry would use simulation and use wind tunnel testing for the final validation to reduce the cost. However, the ability to use digital tools and modelling to reduce the amount of physical testing is limited as modelling for liquid hydrogen systems is immature and not validated due to the lack of experimental data. As such the cost is prohibitively expensive for some organisations which are key to advancing the development of LH2 technologies.

2.3. Capability in Safe Test Design and Operation

Safety remains the top priority and is critical for LH2 testing due to the associated hazards. To maintain the aerospace sector’s safety record there is a need for harmonised standards, clear guidance on working practices and skilled and experienced people to complete test design and operation.

The most effective way to build safety and competence is by providing affordable access to well-managed small- and medium-scale LH2 test facilities. This allows companies and universities to move from design concepts to hands-on experience, accelerating understanding and best practices. Unlike traditional fuels like Jet A-1, there’s little existing knowledge or guidance for LH2 system design, making current development more experimental than requirements driven. Early testing will be crucial to build corporate knowledge, develop design standards, and ensure future LH2 systems meet at least the same safety and reliability as today's aircraft.

2.4. Cost and Access to LH2 Supply

Another major challenge for facilities is obtaining the liquid hydrogen for testing. Currently in the UK liquid hydrogen can only be obtained through ordering a liquid hydrogen tanker of around 2.5 tonnes delivered from Europe or liquefying small volumes onsite from hydrogen gas. Supplying hydrogen in small quantities increases its cost, making current supply relatively expensive per kilogram of LH2 required. This is a major barrier to the UK sector in gaining affordable access to develop low TRL technology and fundamental data and understanding. Additionally, there is increasing demand for liquid hydrogen tanker deliveries across Europe and a constrained supply, not just of the LH2 production capacity, but of the limited qualified drivers, trucks and tanks.

Until such time that LH2 technologies progress to production and operation, the aerospace demand for LH2 will remain sporadic and insufficient to justify the volume of a plant or pipeline as shown in Figure 3, unless other sectors ramp up demand for LH2 as an energy vector. The current planned technology research testing requires LH2 volumes at the lower end of the scale, with most end users requiring 10s of kg/day or less over the next 2 to 3 years. With low demand, the availability of low cost LH2 is unlikely in the near future, as development of large-scale, UK based, supply solutions are not commercially viable. This means the cost of supply and ultimately testing will remain high.

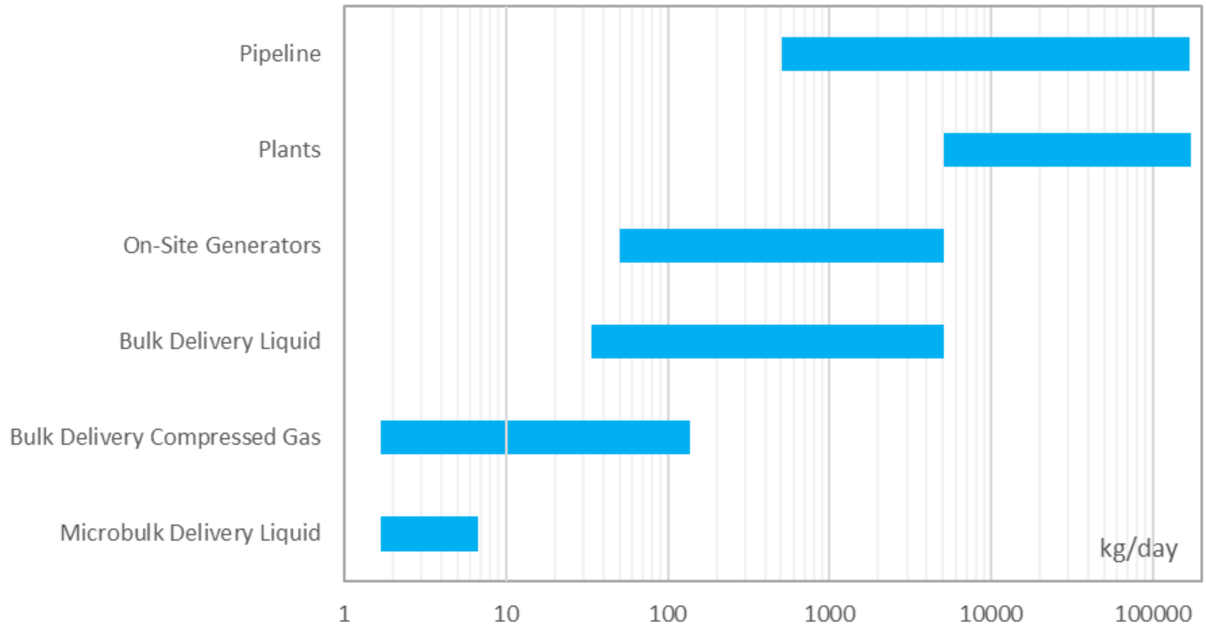

FIGURE 3 – LH2 SUPPLY METHOD V SCALE
(DATA FROM AIR PRODUCTS HYDROGEN SUPPLY)

Safety assurance and standardisation

Gas and LH2 suppliers are committed to ensuring the safety of their customers which for LH2 means carrying out significant customer training to ensure they are competent to take delivery of and handle LH2. This is not necessarily a focus of their future business and so for more and more sites to take delivery of LH2 there may need to be a standardisation and certification for training on being fit to receive LH2.

There are also challenges for hardware where a significant amount of LH2 infrastructure including tanks is leased from the LH2 suppliers. As the sector moves towards building, owning and operating hardware, there will need to be agreed regulations and certification to ensure hardware is fit for purpose and properly maintained. These standardisations could also help with accessing insurance for sites taking delivery of LH2, as this is a challenge as discussed in section 2.5.

Standardised interfaces

As more users come online, LH2 suppliers may start delivering to facilities with hardware that they have not provided. Currently, there is limited standardisation on interfaces, including fittings and procedures and these must be standardised to improve safety and encourage collaboration. A standardised interface will allow LH2 to be delivered more easily in the future, in the same way that Jet-A1 is delivered today via a standard set of interfaces and pressures, and adhering to standards such as SAE's AS5751.

2.5. Safety, Regulations, Standards and Guidance for Testing

The current lead time for approval of a new LH2 test facility is around 12 – 18 months. In order to develop LH2 test facilities a number of regulations across different authorities need to be satisfied.

These include but are not limited to:

- Control of Major Accident Hazards (COMAH) Regulations – for storing hazardous substances
- ATEX Directive – control of explosive atmospheres
- Planning Permission/ Permitted Development Consent – from the local authority

There is limited guidance on how to apply the full suite of regulations to liquid hydrogen facilities and it often involves upskilling local authorities and regulators.

Additionally, there is limited knowledge and awareness of regulations and standards in the operation of facilities. There are few documents relating to best practice in handling and storing hydrogen gas and liquid hydrogen, most of which have been developed for different use cases. There is no overarching source for regulatory guidance and therefore currently test sites are using best practice from multiple standards combined with their own risk assessments/ HAZOPs and local procedures.

Typically, these standards have been written by industry experts in working groups sponsored by the larger organisations in a sector. Currently there is an insufficient mass of skilled and experienced LH2 practitioners in the UK aerospace industry to generate this type of standard. Regulatory bodies like the Civil Aviation Authority (CAA) are advancing their hydrogen knowledge including through the CAA's Hydrogen Challenge and are beginning to establish working groups. Standards are beginning to be developed, for example AIR8466 from the SAE for *Hydrogen Fuelling Stations for Airports, in Both Gaseous and Liquid Form*. This document is described as establishing a baseline and is expected to evolve over time as the technology and industry understanding matures.

The proliferation of standards impacts their usefulness, as the purchasing of multiple standards is prohibitive for SMEs, academics and even for larger organisations. For example, *ISO 21013-3:2016 Cryogenic vessels — Pressure-relief accessories for cryogenic service,* is expensive and once purchased can only be accessed by one user. This standard is fairly exhaustive and needs regular referencing when designing and peer reviewing a cryogenic safety relief system, therefore multiple licenses are typically required by an organisation. This is one example of many areas that need to be considered. As such this cost is relatively significant and is creating a barrier to entry for many.

Availability of standards, guidelines alongside standardisation of equipment, interfaces and training could also help with accessing insurance for sites taking delivery of LH2 which also represents a challeng. Currently it is difficult to quantify the risk to generate insurance costs and therefore sites are finding it difficult to obtain insurance.

There would be a benefit to the industry in harmonising the relevant sections of existing standards, to help to provide LH2 practitioners with a common set of guidelines. As the fundamental understanding of health and safety through research develops further these guidelines and standards can be continually updated. Developing a community of practice around regulations for test facilities would also help to build a critical mass of experts who could shape the development of regulations for on aircraft technologies and airport operations.

2.6. Availability and Cost of Equipment / Hardware

Sourcing equipment for LH2 testing is expensive and often involves long lead times due to a limited supply chain and low historical demand. Off-the-shelf LH2 rated components are generally unavailable, requiring buyers to conduct their own material assessments and manage associated risks. Although the market is starting to respond to growing interest, bringing more certified equipment online, costs remain high and lead times can exceed six months. The lack of demand also limits the equipment supplier's ability to invest in efficient manufacturing, keeping prices high.

Developing UK-based LH2 testing infrastructure would reduce reliance on overseas suppliers and attract international manufacturers seeking certification. Test facilities naturally build up valuable, reusable equipment over time, making future testing more affordable, especially when infrastructure is centralised. For aerospace applications, where testing must also simulate altitude, vibration, and extreme conditions, the need for specialised LH2 compatible systems is even greater although this requirement will evolve as technologies progress towards TRL 6.

2.7. Making a Commercial Case for Test Facilities

To generate the levels of investment required, facilities must show strong business cases that highlight the return on investment or value for money. This would often take the form of a clear future userbase and committed user agreements.

However, the current research and development space around liquid hydrogen is still immature and securing these is difficult as very few users have initiated their first tests in liquid hydrogen and do not have a clear view of future needs. Combined with the other challenges for users highlighted above, this presents significant barriers to entry.

Given the immaturity of knowledge and data around LH2, and lack of tools for digital modelling and simulations, research and development will need to rely on an iterative process of testing. Together with the high cost of LH2, this reduces the ability of test users (industry, research and academia) to commit to a long-term LH2 test plan.

Typically, smaller scale, academic infrastructure is more suited to EPSRC funding, however the cost of LH2 facilities is mainly too high for typical EPSRC funding. Alongside some of the challenges above, with the need to maintain safety while experience and capability develops in the handling and operation of LH2, this points to the case for larger more centralised facilities. But with the backdrop of it being difficult to make a commercial case this indicates a potential need for government intervention.

3. Forecast Demand and Infrastructure Provision

There is a large potential user base for LH2 test facilities across the aerospace sector, ranging from academics looking to carry out fundamental scientific research to OEMs looking to complete full system tests. However, the long-term demand from these users is uncertain as set out in previous sections.

As a response to there being no clear provision of centralised open access facilities, but users needing to do testing, there are numerous proposals for the development of experimental LH2 facilities, some of which are potentially duplicative. Despite the large number of proposals there are few operational today and only a small number which have progressed to funding given the challenge in developing business cases without a clear view of future demand (see section 2.7).

Facilities of different scales are needed and a large range of supporting infrastructure is required to enable certification testing of aircraft systems.

3.1. Demand

The following data is drawn from the survey and workshop aimed at capturing LH2 supply and demand from end users across the aerospace sector. Figure 4 presents the estimated annual LH2 requirements for testing, broken down by consumer type. The numbers in each column indicate how many organisations are operating at each scale. The data highlights a near-term focus on small-scale testing, primarily academic research in materials, thermofluids and component-level testing. However, a single organisation conducting system-level testing can significantly skew the LH2 demand.

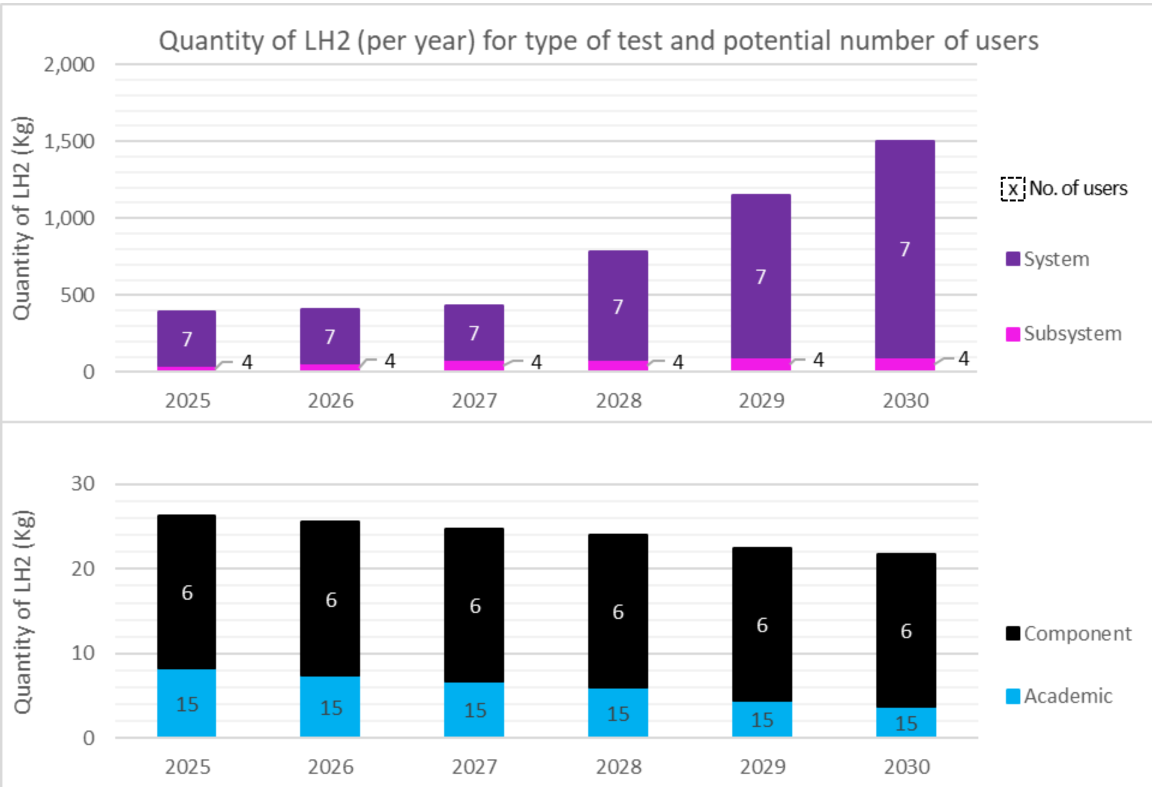

FIGURE 4 – PROPORTION OF EACH TYPE OF TESTING REQUIRED

The consumer type is split into four categories of testing needs which is defined by the scale of testing and LH2 required and broadly aligns to types of stakeholder organisations within the aerospace sector. Across these categories there are different testing requirements which can vary the type of equipment needed and the volume of LH2:

- Testing to determine fundamental properties and data points
- Testing to prove function and performance of technology and products under different conditions
- Endurance testing of products to aerospace requirements
- Environmental testing of products in representative operating conditions
- Failure cases from component to whole aircraft to operational environments

Figure 5 shows the available supply as it currently stands for LH2 and the proposed increase in capability over the next five years, which indicates there is more than enough capacity. However, some of this exists at larger facilities that are not yet set up or affordable for the consumers who need only a few kilograms for a test as they must purchase a minimum order quantity of 2500kg at a cost of over £100,000. The challenge in the near term is enabling smaller scale tests with affordable and safe access to LH2 test capability.

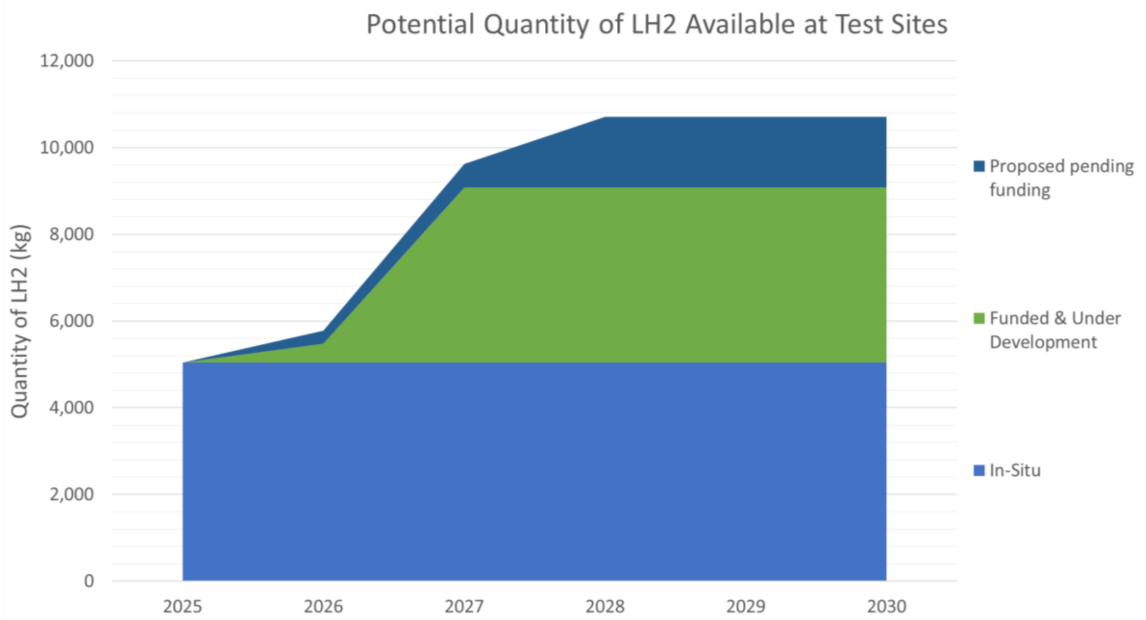

FIGURE 5 – SUPPLY OF LH2 TEST CAPABILITY (KG/DAY OF TESTING)

3.1.1. Academic (<10 kg)

Universities must conduct both experimental and coupon-level testing to support and inform fundamental research. In the near term, there is a need to understand the material, thermofluid and health and safety behaviours of hydrogen[1] across its full operational temperature range; from high temperatures exceeding 1000K, as may be required for high temperature fuel cells and turbines, to subcooled liquid hydrogen (LH2) in the range of 10–20K for storage and transportation. In parallel, PhD and postdoctoral projects will be launched to explore and innovate early-stage (TRL 1–2) technologies.

[1] The HCN research reports set out the fundamental research priorities that need to be addressed

These research activities typically require only small quantities of LH2, often less than 10kg per test, and in many cases just a few grams at flow rates well below 0.2 g/s. However, even tests involving a few grams of LH2 may demand several kilograms initially to cool down the test apparatus.

Obtaining high-fidelity data for these research phenomena requires specialised laboratory equipment and expertise such as cryogenic and hydrogen-compatible densimeters, viscometers, differential scanning calorimeters and cryogenic spectroscopic instruments. The sensors for measuring accurately also need to be tested to validate their behaviour.

Small-scale test setups must be carefully designed to optimise thermal insulation and minimise the thermal mass that needs to be cooled. Many setups will benefit from the use of cryostats to thermally isolate the test coupon or system from the surrounding environment. Precision in boundary condition control, accurate measurements, and rigorous calibration are critical. However, cryogenic hydrogen instrumentation and sensing remains a niche domain and needs to be made more accessible and standardised to enable reliable data collection. Developing standard interfaces for tests would allow for repeatability and re-use of equipment.

Making this capability accessible and affordable to universities and SMEs is essential for accelerating the UK's leadership in liquid hydrogen system development.

A good example is the progress made by Washington State University's HYdrogen Properties for Energy Research (HYPER) Lab. This is a pioneering research facility dedicated to advancing hydrogen technologies, particularly in cryogenic environments. Established in 2010, it stands as the only cryogenic hydrogen research centre in U.S. academia. They specialise in LH2 storage, propulsion, and energy systems. Its research spans various sectors such as aerospace, defence, clean energy, and fusion energy and is used and engaged with by global organisations including some of the larger industrial companies in the UK.

3.1.2. Component (10s of kg)

Aircraft cryogenic hydrogen storage and fuel systems will consist of hundreds of components, each of which must be matured and validated to at least Technology Readiness Level (TRL) 4 before integration into a full system architecture. Once proven, these components and the associated intellectual property can be commercialised for LH2 applications across the aerospace sector and beyond.

Many of these critical components do not exist for aerospace applications today, and many of the aerospace primes are citing critical gaps in the supply chain. Component manufacturers are a key part of the UK aerospace sector, providing long-term economic value to the UK. As market exploitation for aerospace has a long lifecycle and new entrants are required it is essential that component level testing infrastructure is both available and affordable to stimulate innovation and enable the scaling of UK SMEs in the hydrogen sector.

Functional and performance testing at the component level is critical. Given the rapid pace at which equipment manufacturers and system designers are evolving LH2 components and architectures, test facilities must be flexible enough to accommodate a wide range of configurations and physical phenomena. This flexibility should be balanced with standardised interfaces wherever possible for example, standardising LH2 supply connections, delivery controls, venting and safety relief systems.

The nature of testing will vary significantly depending on the component and its intended function. While each test setup may require bespoke configurations most will involve LH2 usage on the order of 10s of kilograms. Testing components such as pipes to evaluate heat flux, thermal insulation, pressure drop and structural integrity can demand greater volumes, as can the evaluation of pumps, valves and other dynamic elements. Similarly as components move to endurance testing greater volumes are required. To minimise both cost and environmental impact, it is essential that LH2 used in these tests is not vented but instead recirculated and reliquefied. A closed-loop system with integrated reliquefication capability will enable efficient and sustainable testing by allowing reuse of the LH2.

At lower TRLs, similar to academic research, component testing will often require a cryostat to isolate the core technology from environmental effects. As components mature to TRL 4 and beyond they will increasingly be capable of operating within standard enclosures or relevant environmental conditions, reducing the need for isolation.

Most LH2 component testing in the UK is concentrated at Element's test facilities at Kemble Airfield, which offers flexibility in terms of multiple cryostats, and allows for rapid reconfiguration of interfaces and setups to accommodate a wide range of test scenarios.

As component designs progress toward TRL 6 and become ready for market adoption, aircraft systems will need to undergo formal environmental testing in accordance with RTCA DO-160 standards. To date, this level of rigor has not been required; flight trials have typically operated under experimental permits, with the testing risks largely borne by the organisations conducting the flights. However, as systems mature and approach commercial deployment, the need for standardised, certified environmental testing will become a requirement.

This transition is far from trivial. Existing test infrastructure such as shaker tables for vibration testing or electromagnetic compatibility (EMC) chambers were not designed to accommodate the safety risks associated with hydrogen, particularly LH2. Significant modifications or entirely new facility designs will likely be required to ensure safe and compliant testing environments for hydrogen systems.

While these capabilities are not immediately required, by the time they are, the supporting industry and business cases will be more developed. This maturation will make it easier to justify and secure investment in the necessary infrastructure to support hydrogen component certification at scale.

3.1.3. Subsystem (100s of kg)

Companies developing storage, fuel systems and powertrains will require significantly larger volumes of LH2, necessitating more flexible and scalable supply options such as bulk trailer deliveries. While powertrain testing typically consumes hydrogen, most other system testing should aim to capture and reliquefy vented hydrogen. Doing so not only substantially reduces operational costs but also minimises greenhouse gas emissions, supporting both sustainability and affordability.

Currently, subsystem level testing is essential to validate the functionality and performance of both LH2 storage systems and integrated powertrain components. These tests currently remain relatively basic while system architectures are tested at a fundamental level and 1D modelling tools are validated. As fuel system architectures are downselected, they will need to mature and become more detailed and accurately reflect the correct system boundary conditions as they get closer to flight and certification. Currently, the primary focus is to validate optimal system architectures and demonstrate mitigation of critical failure scenarios, especially those relevant to early-stage flight trials.

Demonstrating subsystem level performance at TRL 4 is particularly important for securing investment and customer support to progress to the next stage of development. Ensuring that these test facilities are accessible and affordable across UK industry is vital to unlocking investment, accelerating innovation, and retaining valuable intellectual property and skills within the UK.

Flow rate requirements for subsystem testing vary from approximately 2 g/s to 50 g/s, supporting power levels from 100 kW up to 3 MW. Most current systems operate below 10 g/s but are expected to scale up over the next few years. Some high flow scenarios such as rapid refuelling may demand short bursts of much higher flow rates. The venting and safety systems for these facilities would need to be capable of handling these higher flow rates. System level failure events and ultimate/limit load testing under cryogenic conditions will need to be performed at specialised facilities with larger safety zones, such HSE's Buxton site and DNV's Spadeadam site.

Some subsystem tests will include operational powertrains, which require appropriate loading mechanisms either electrical or mechanical via dynamometers. Given the close proximity of such high-power equipment to LH2 infrastructure, these setups will likely require purpose-built test facilities specifically designed for the safe integration of cryogenic hydrogen and high voltage or high-power systems.

Over the next few years, both component and system architectures are expected to mature and likely converge toward optimal configurations. As this happens, the focus of testing will shift toward more rigorous validation against standards such as RTCA DO-160. At this point, additional equipment such as shaker tables for vibration testing and dynamometers for powertrain loading will be required at a larger scale to simulate real world aircraft environmental conditions.

3.1.4. System (1000s of kg)

System level testing will often include endurance or life testing and hence require larger total volume of LH2 consumption over a longer period of time. This can utilise existing trailer deliveries and the volumes are significant enough for the large LH2 and gas suppliers to plan into their forecasts/ delivery schedules. At this scale there may be larger sitewide infrastructure required as COMAH regulations come into play and system boil off efficiencies have a more significant impact on the operating costs. System level testing brings together all major elements of the LH2 fuel system and powertrain often including integration with the aircraft platform itself. There is limited immediate technical need for full system integration testing, although these can be useful for demonstration to investors, to wider ecosystem stakeholders and for raising public awareness. Fuel and power subsystems can continue to be tested independently, provided their interface requirements and performance metrics are clearly defined and validated.

For system level testing the infrastructure burden may be somewhat reduced compared to early-stage component testing, as the systems under test are more complete, self-contained, and capable of managing their own operations. These facilities should be designed to accept bulk LH2 deliveries and operate safely at scale in line with relevant regulations such as COMAH.

Some system level tests will essentially be scaled up versions of the subsystem tests previously discussed, requiring large LH2 volumes but not necessarily high flow rates. Once LH2 is onboarded, the integrated fuel system will regulate flow and pressure to the powertrain. In most scenarios, a dynamometer will be needed to apply load to the output of the power system.

To date, most aircraft system level testing has been performed using gaseous hydrogen, with only a few early-stage efforts beginning to fly LH2. Flight testing is an important step in demonstrating operational capability, growing certification and regulatory expertise and publicity for adoption of LH2 for aerospace. Ground-based testing at subsystem and system level remains critical for technology development where system architectures are still evolving and performance is improving rapidly.

3.1.5. Cross Sector Testing

The aerospace industry is not alone in the need to undertake testing to further advance its understanding of liquid hydrogen and develop technologies for LH2 use. Collaboration with colleagues in aviation will be essential for testing and demonstration especially on refuelling and safe handling at airports. Other sectors may have different requirements, but some of the fundamental physics will be the same. In some cases other sectors may also be able to move faster than the aerospace industry, which can drive an earlier return on investment and act as a catalyst. Therefore, collaboration with other sectors, in particular on the baseline physics of thermofluids and material properties is imperative. The gaseous hydrogen industry is beginning to utilise LH2 for transportation and to help with the significant cooling requirements required to overcome the Reverse Joule Thompson effect during fast refuelling of gaseous systems. Universities will typically work across sectors and therefore should be a means to encourage collaboration across sectors within the UK. Other obvious sectors to work closely with are Marine, Automotive and Energy, particularly those already exploring or utilising gaseous hydrogen.

3.2. Infrastructure Provision

Figure 6 below shows the geographic location of the three existing test facilities with LH2 capability along with funded sites under development and proposed sites awaiting funding approval. Figure 7 shows the timeline for the planned and proposed sites against their scale of LH2 capacity.

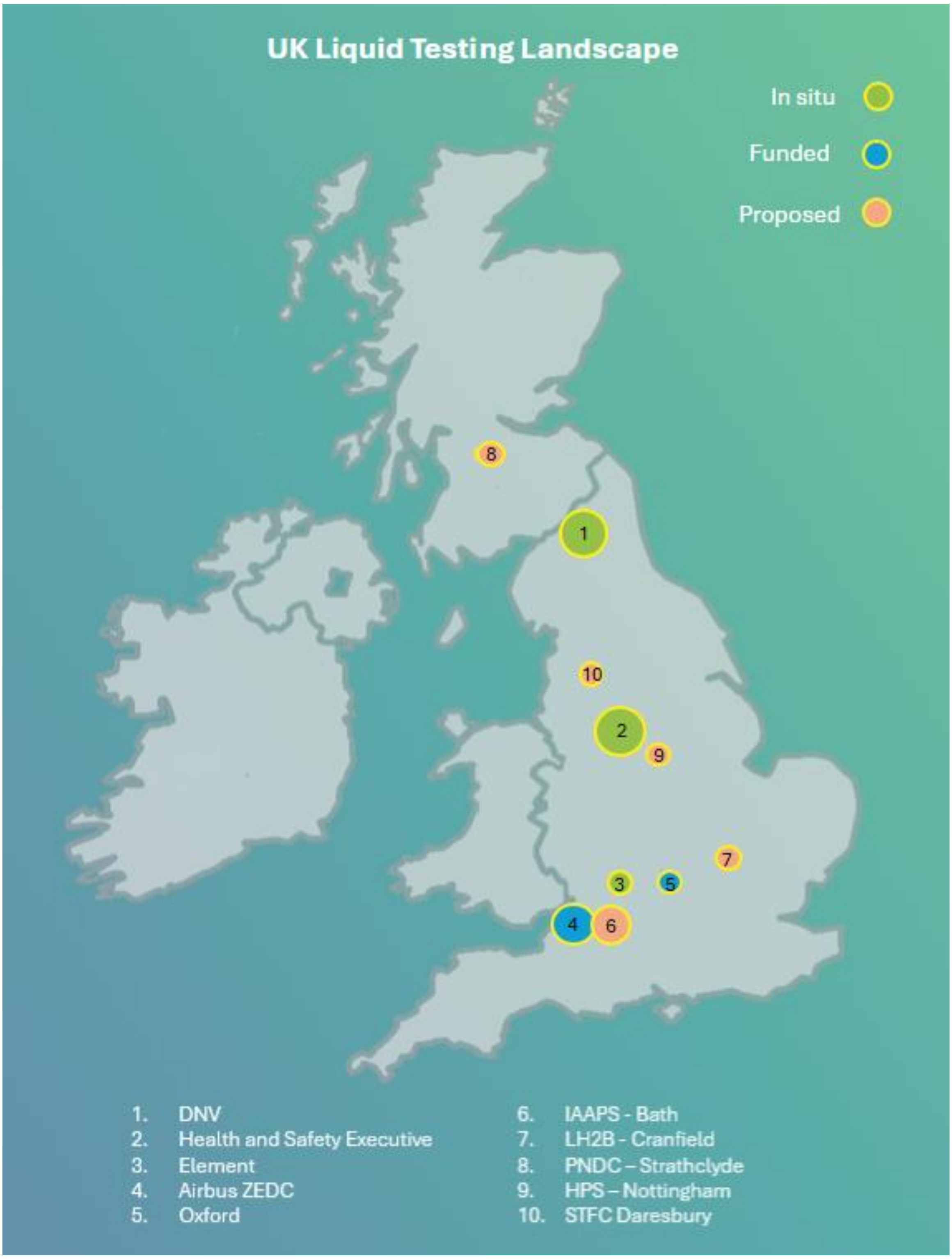

FIGURE 6 – CURRENT AND PROPOSED LH2 TEST FACILITIES (BUBBLE SIZE DENOTES LH2 CAPACITY KG/DAY)

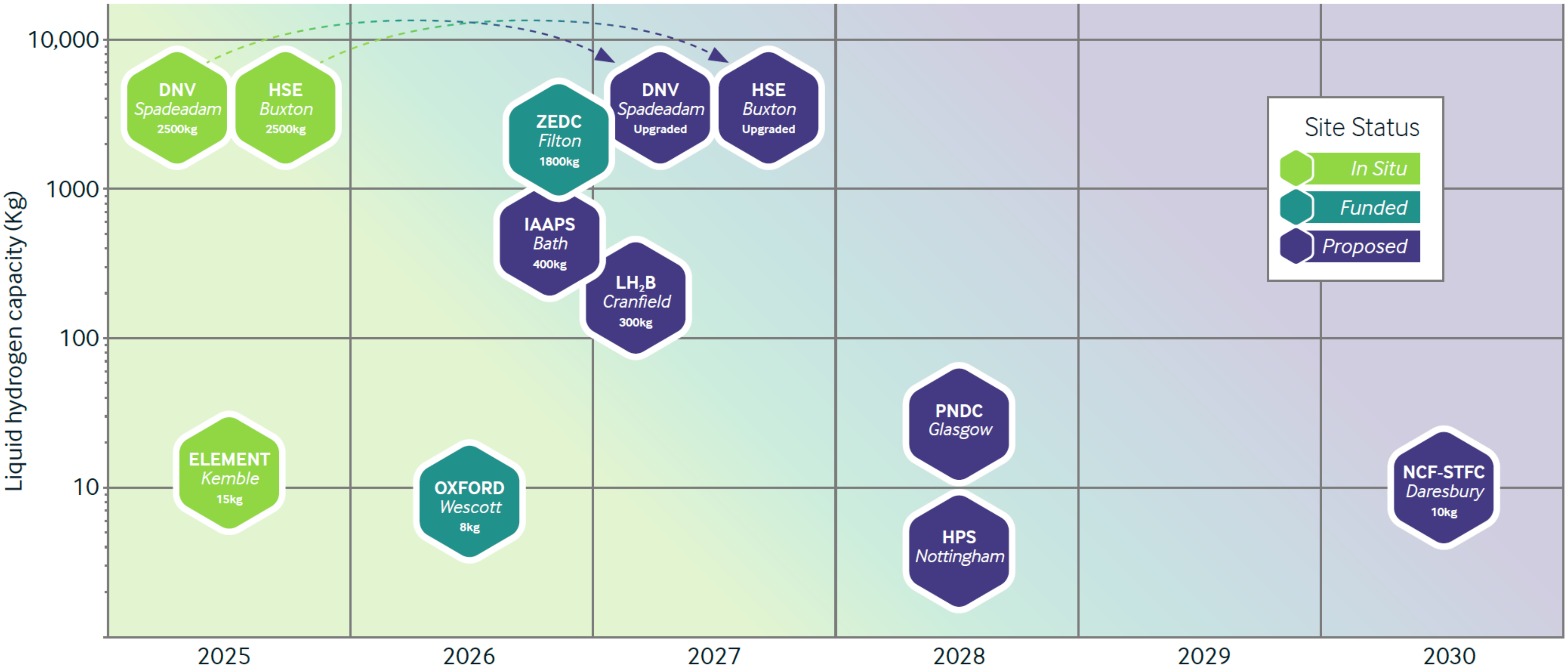

FIGURE 7 – FACILITIES TIMELINE AND LH2 STORAGE CAPACITY AT UK FACILITIES

3.2.1. DNV

Spadeadam Research and Testing Facility	**Gilsland, Cumbria**	yura.sevcenco@dnv.com
Description:		Key Specs
		IN SITU
Site is large with few nearby risks and able to perform large-scale hazardous testing. LH2 is delivered to site in tankers and delivered straight into the test setup. Typical test carried out - Explosions, Boil-off, loss of containment, BLEVE, Jet-Fire, Technology demonstrators, re-fuelling.		Capacity - 2.5t LH2 trailer Flow rate – as required Pressure – 100 Barg Large-scale and hazardous
		PROPOSED
DNV is exploring having a liquefier onsite to be able to service smaller test capability. This may be coupled with expansion of the cryogenics facilities to store hydrogen produced for small/medium tests, or excess from tanker deliveries.		TBD

3.2.2. Health and Safety Executive (HSE)

HSE	**Buxton, Derbyshire**	nigel.moss@hse.gov.uk
Description:		Key Specs
		IN SITU
Large site (500 acres) and able to carry out large-scale testing using 200m exclusion zones if required. LH2 is delivered to the test location area in road tankers (up to 2.5 tonnes).		Capacity - 2.5t LH2 trailer Flow rate – as required Pressure – 10 Barg Large-scale and hazardous
		PROPOSED
Early stage discussion about having a liquefier onsite to be able to service smaller test capability. Have 500l dewar for smaller scale transfer of LH2. Actively seeking funding to develop and expand current LH2 facility as a National Cryogenic Test Centre. Plans include options to enable smaller scale testing to be carried out.		Capacity - 2.5t LH2 permanent tanks Flow rate – 500 g/s Pressure – 10 Barg Large-scale and hazardous

3.2.3. Element

Element	Cotswolds Airport, Kemble	mark.eldridge@element.com
Description:		Key Specs
The Element LH2 test facility at Kemble forms part of a wider H2 portfolio of evolving test capability in relation to gaseous and liquid hydrogen across Element (both in the UK, Europe and USA). This roadmap includes modelling and simulation, environmental testing (incorporating temperatures and pressure) for a range of technologies, fuel systems – design, build and test, safety consultancy and application, and materials characterisation for both gaseous and liquid hydrogen – covering frame build, design, build and operation. Operations cover a variety of end markets, from space, defence, transportation, oil and gas and aerospace.		**IN SITU** Liquefaction - 12 kg/day Capacity – 15 kg Flow rate – as required Pressure – Each rig is designed to customer requirements Flexible & Tailorable
LH2 storage capacity has been temporarily expanded for some tests, this could become a more permanent feature if higher capacity of LH2 is required.		**PROPOSED**

3.2.4. Airbus Zero Emission Development Centre (ZEDC)

Airbus ZEDC	Bristol, Filton	graham.read@airbus.com
Description:		Key Specs
Small-scale learning platform for component testing with GN2, GH2 & LN2 capability.		**IN SITU** Gaseous H2 + N2
Funded project to install 3.6 tonnes of onsite LH2 storage capacity with EIS in Q3 2026, large test area with multiple test bays and data acquisition available for external testing from Q2 2027. LH2 delivered to site by tanker.		**PROPOSED** 3.6T trailer Flow rate 1500g/s

3.2.5. Oxford Wescott

Oxford Thermofluids Institute	University Of Oxford	peter.ireland@eng.ox.ac.uk
Description:		Key Specs
Materials testing down to 28K, heat exchanger testing with LN2, gaseous H2 materials testing. Instrumentation being developed. Low TRL LH2 fluid dynamic, heat transfer and materials tests. This site also has a large NWTF2 tunnel which will provide open access. LN2 testing at 0.25kg/s at 70 bar.		**IN SITU** Liquefaction - 5 kg/day Capacity – 16 kg Flow rate – as required Pressure – Dewar 4-5 Barg
Upgrade proposed in 2026 to 16kg of LH2 capacity then 32kg		**PROPOSED** Liquefaction – 10-15 kg/day Capacity – 32 kg Flow rate – TBD Pressure – up to 70 Barg

3.2.6. IAAPS

IAAPS - ARCHER	Emersons Green, Bristol	enssa@bath.ac.uk
Description:		Key Specs
High power dynamometers for testing complete power trains, lots of experience integrating automotive power trains for testing and development up to 2MW capacity. Currently have cryogenic helium onsite with the use of Stirling cryogenics cryomech cold heads		**IN SITU** Electrolyser – 240kg/day Gaseous H2 Capacity 270kg Pressure 30 Barg
LH2 delivered by road tanker, proposed liquid hydrogen feed to test LH2 components i.e. pumps and valves, heat exchangers. Developing small-scale facilities to test sub-components- i.e. bearings seals etc.		**PROPOSED** Planned 420kg in 2025, increasing to 1,500 kg by 2028

3.2.7. Cranfield University

Faculty of Engineering and Applied Sciences	Cranfield University	j.horsley@cranfield.ac.uk
Description:		Key Specs
From 2026 this site plans to have large experimental sites for aircraft fuel systems and tank testing, slosh and negative-g testing, pumps/sensors/actuators' testing, modelling correlation, delineated areas for confidentiality, smaller scale test areas for material coupons and structures, large LH2 flow capability, and in the future simulations of LH2 handling for airports and aircraft refuelling.		**PROPOSED** Liquefaction – 40 kg/day Capacity – 300 kg Flow rate – 50 to 300 g/s Pressure – 4 Barg

3.2.8. Power Networks Demonstration Centre (PNDC) Strathclyde

University of Strathclyde	James Weir Building, Glasgow	Daniel.j.cutting@strath.ac.uk
Description:		Key Specs
Focus on electrical power systems testing (electrical distribution, fault throwing, power electronics/machines testing). Experience in modelling and testing of gaseous hydrogen fuel cells and energy system level projects on hydrogen system (make-move-use).		**IN SITU** Configurable Electrical distribution network 2.5MVA s/stn & LV network 1MVA DC power supply 1MVA AC/DC power supply (can be combined to offer 2MW DC) Real-time digital simulation 2 x 1MW dynamometers Capacity - 80 kg of GH2 Pressure – 12 Bar Flow – 2.5 g/s
Increasing gaseous storage capacity, flow and pressure capability. With LH2 supply being a potential energy vector, the facility plans to supply onsite to enable full systems testing in the future.		**PROPOSED** Capacity - 160 kg of GH2 Pressure – 20 Barg Flow – 8.3 g/s

3.2.9. University of Nottingham

Hydrogen Propulsion System Laboratory	University of Nottingham	mark.pacey@nottingham.ac.uk
Description:		Key Specs
In the first phase, small-scale testing for materials testing and liquid hydrogen property studies. Currently partner with HSE Buxton for these tests, simultaneously developing their own capability. Second phase plan to offer component testing using larger quantities of LH2. In parallel, we will develop small-scale production from gaseous hydrogen delivered to site.		**PROPOSED** Small-scale liquefaction

3.2.10. STFC Daresbury

National Cryogenics Facility	Daresbury, Cheshire	rachel.james@stfc.ac.uk
Description:		Key Specs
Current helium cryoplant onsite serving needs of particle accelerator and quantum computing applications. Provides liquid helium at 2K. Closed loop system with onsite liquefaction. Lab space and support available for trials at cryogenic temperatures.		**IN SITU** Flow rate; ≈3g/s Helium at 2K
National Cryogenic Facility (NCF); a user facility to meet needs of a range of industry sectors (e.g. quantum, HTS and aviation). Includes x100 expansion of current cryoplant and large-scale lab facilities to test cryogenic processes and materials. Will be able to provide large-scale cooling at a range of temperatures including 20K using Helium. Anticipate will also offer small-scale test capability (for materials and components) with LH2. Anticipated availability 2031		**PROPOSED** Lab Space; 4,000m^2 Cryo plant: 10kW Helium cryoplant (4.5K). Exact spec to be confirmed based on user needs.

4. Supply of Liquid Hydrogen for Testing

Developing LH2 infrastructure, particularly for liquefaction, storage, and distribution is highly capital intensive and carries significant risk. For investors and developers to commit, they need confidence in the market. This means a stable, predictable demand for the LH2 produced. Offtake agreements or long-term commitments from key sectors (e.g. aviation, shipping, heavy transport, or utilities). It also requires proven commercial viability, ideally demonstrated through pilot projects or reference facilities. Without these assurances, investment may be seen as speculative and costly facilities to develop with the risk of being underutilised.

At the same time, companies and government are reluctant to commit to the production of LH2 at scale until they have confidence in the technology and demand. They want to see demonstrations of the technology's performance and reliability as well as evidence that LH2 is cost-competitive with alternatives energy vectors.

Therefore, as discussed in section 2.4, one of the biggest challenges for test facilities is the LH2 supply especially in smaller volumes and some potential options are discussed below. As facilities increase capacity and the volume of hydrogen stored increases, the potential impact of any accident also increased. Therefore, Control of Major Accident Hazards Regulations (COMAH) begins to come into force. COMAH doesn't apply to road tankers whilst in transit but when onsite at any test facility the contents of the LH2 road tanker does add to the current onsite storage. Once the combined total reaches five tonnes, including consideration of other restricted substances stored, the site needs to comply with the lower tier COMAH regulations.

4.1. Large-Scale Supply

There are initiatives to achieve clean hydrogen prices of less than £10/kg in the near term; for example, the US department for energy is targeting $2/kg by 2025 and $1/kg by 2030 (Source). To achieve this, large-scale capital expenditure (CAPEX) is required including from potential LH2 suppliers which need a clear demand signal and offtake agreements. Until then a transition period is needed where small- or medium-scale LH2 production is increased to support consumers. As demand for LH2 increases, the economic argument for CAPEX becomes more favourable, enabling large-scale supply to become more widespread.

Typically, a large-scale plant is located where there is a large enough regional demand, and the plant will act as a hub for tanker deliveries. Large airports such as Heathrow, currently consumes approximately 18,000 tonnes of kerosene per day. This equates to approximately 6,500 tonnes of LH2 per day to represent an equivalent flowrate of energy. At this scale either a localised liquefaction plant would be required onsite or a pipeline from a regional hub.

Large-scale LH2 supply is expected to be defined as the production and/or liquefaction which is upwards of thousands of kilograms of hydrogen per year. For example, Air Products has received development consent to build a plant in Immingham, Lincolnshire which could supply 210 tonnes of hydrogen per day liquefying 35 tonnes. Air Products already has a hydrogen liquefaction plant in Rotterdam and is building a second one to be opened around 2025. Linde also has multiple large-scale liquefaction facilities, such as the Leune plant in Germany. At Leune, Linde currently liquefies between five and ten tonnes of hydrogen per day.

Large-scale liquefaction requires infrastructure to be developed or supported alongside the liquefaction process. Either the hydrogen can be created onsite through electrolysis or ammonia cracking like at Immingham, or it can be brought in from shipping or, more likely, pipelines. Significant power infrastructure is also required to support this. Therefore, large-scale liquefaction plants are usually co-located at ports or refineries to minimise the CAPEX required to develop new systems.

Larger-scale liquefaction equipment has higher energy efficiencies than those found at medium- or small-scale ones although the fundamental technology is the same across scales. A limited number of companies can provide equipment such as suitable heat exchangers, expansion turbines, or cold boxes at the required scales. Hydrogen boil-off management is considered at these scales through re-liquefaction. Finally, transfer equipment to move LH2 from the liquefaction plant to storage vessels, tankers, or on-road shipping transport is needed. All of these factors contribute to the large footprint and CAPEX requirements however, longer-term gains in efficiency and sales result in decreased LH2 costs.

4.2. Medium-Scale Supply

Medium-scale supply is considered to be approximately 2.5 to 3.5 tonnes of LH2, equivalent to the amount of LH2 capacity of an insulated road tanker. These tankers do not currently accommodate lower volumes, meaning that this approximate amount of 2.5 tonnes is the smallest individual unit available. Costs for each tanker are estimated, in March 2025, as being between £50,000 and £200,000. While using tankers enables medium-scale testing and can be suitable for companies performing system-level testing, the hydrogen in the tankers must be used quickly or transferred to a suitable insulated storage tank onsite. In the UK, a small number of sites currently use tanker deliveries as the demand for that amount of hydrogen is infrequent. As an example, the Health and Safety Executive (HSE) have trailer deliveries to their Buxton site for health and safety investigations and research.

4.2.1. Bulk Delivery by Tanker

Some multi-national companies sell both GH2 and LH2 in the UK. The price secured will depend on several factors, including the likely total demand being procured over time. On the range of estimate for a tanker above this gives a price per kg of between £20 - £80/kg if the whole trailer is utilised. But considerations of chill down, boil-off and residual liquid/ losses during transfer means the volume for testing and therefore the price/ kg for test will be higher.

If only some of the LH2 is required to be used over a short duration test campaign, then a method of storage needs to be considered. Some LH2 suppliers, can deliver in trailers or tankers insulated with LN2 which can hold the LH2 for up to 200 days onsite, although these come at an additional cost of £200,000 per delivery. The alternative is to purchase one of these trailers at cost of £1.6m, or a permanently installed storage tank in the range of £300,000 to £900,000 for between 500kg – 3000kg of storage. A local storage tank would remove this additional £200,000 of cost per delivery and make it more affordable in the long term for sites that have a regular ongoing demand.

The **British Oxygen Company (BOC)** has been part of **Linde Plc** since 2006. In the UK BOC Linde currently produces gaseous H2 but not LH2. LH2 is brought in trailers from their Leuna Chemical Complex in Germany. BOC have indicated that investment in LH2 supply for the UK will occur when there is more confidence in the demand.

Air Products, headquartered in the US, is one of the largest hydrogen producers in the world. Honeywell acquired Air Products' Liquified Natural Gas Process Technology and Equipment Business in 2024. Honeywell are also well established in the aerospace sector. Air Products is also investing in hydrogen production infrastructure in Wales (link: Air Products Drives UK Hydrogen Market Growth with £6.5m Investment). At the HCN Test Infrastructure workshop in March 2025, Air Products highlighted some areas of hydrogen support and development, for example, working with Gatwick Airport on long term infrastructure for when LH2 demand is required at commercial airports.

Air Liquide are headquartered in France and have large-scale hydrogen liquefaction capabilities. The company has been awarded a grant of €110m from the European Innovation Fund for its ENHANCE project in the port of Antwerp-Bruges, Belgium. This project aims to produce and distribute low-carbon and renewable hydrogen derived from ammonia. At the HCN test infrastructure workshop, Air Liquide showed some of the ongoing and planned large-scale European hydrogen liquefaction projects. Air Liquide also gave details of its LH2 trailer; a key example of the medium-scale options available for UK LH2 supply while there is no large-scale liquefaction capability in the UK.

4.3. Small-Scale Supply

Small-scale supply is considered to be LH2 supplied up to 1000 kilograms, a fraction of that which is available from an LH2 trailer. Small-scale supply is particularly relevant for research and academic organisations or small-medium size enterprise (SME) companies, who need LH2 for experimental work or component testing. Such organisations often lack the initial funds, space, or requirement for the volume of LH2 that comes in a tanker. This presents a risk to advancing fundamental experimental work to understand LH2 and its interactions with materials and the environment which is critical to enabling larger-scale LH2 usage and development.

Current options for small-scale supply in the UK is either individual site liquefaction or the delivery of a full tanker. Other options being considered are covered further below, with many of these solutions requiring the test location to have LH2 storage vessels. One example of a UK company specialising in cryogenic storage vessels is Wessington Cryogenics. They provide off-the-shelf products for storing LNG, LOX and LCO2 and they have more recently been involved in the manufacture of LH2 tanks for UK companies. Such a company could supply some of the onsite infrastructure needed and the mobile tanking equipment for deliveries and 'milk rounds'. It would also improve the maturity of the UK supply chain in the manufacture of LH2 infrastructure.

4.3.1. Bulk Delivery and LN2 Insulated Trailers

Similar to the medium-scale supply solution, bulk deliveries of around 2.5 tonnes can be made with a trailer left at the testing site. If the trailer insulated with a LN2 shield, this increases the hold time up to approximately 200 days with an additional hire cost of £200k per delivery. These tanks need replenishing with LN2 as this boils off, but it would allow the LH2 to be shared by multiple users at a test site during the 200 days. If the contents of the trailer or tanker were fully utilised through sharing across multiple users, the price could be between £100/kg and £160/kg, which is more affordable than each test buying its own delivery. Considerations around chill down, boil-off and residual liquid/losses during transfer will reduce the volume available for testing and therefore the price/ kg for test will be higher.

4.3.2. Milk Round

A ‘milk round’ is an option in which a tanker delivery of 2.5 – 3.5 tonnes could do multiple drops of LH2 and transfer smaller volumes to smaller permanent tanks or dewars. While this concept seems simple, the reality of managing the logistics and timing of deliveries for multiple locations on a given day with tests ready to receive the LH2 would need a careful coordination alongside the commercial aspects of purchase commitments for a tanker cost to be shared.

4.3.3. Bulk Break/ Splitter facility

A ‘bulk-break’ or ‘splitter’ facility could allow for one large tanker of LH2 to be delivered from a site in mainland Europe and ‘split’ into smaller quantities for delivery. An example of such a facility would be the BOC site in Thame where larger quantities of liquid oxygen are divided into smaller quantity dewars for distribution for a variety of medical needs. A splitter facility would act as a hub and spoke model for which a company would oversee the safe operations and ensure that the LH2 could be transported and stored safely. This would require investment in appropriate vehicles and trained operators for transportation.

Developing this infrastructure would also increase the UK’s knowledge and skills in operating this fuelling infrastructure at a smaller and more affordable scale, hence preparing the UK for scaling up as the demand increases.

4.3.4. Small-Scale Liquefier

Onsite small-scale liquefaction can be tailored to meet individual site demand and does not need to be linked to a wider infrastructure network in the way that large-scale liquefaction requires. Many of the companies that support large and medium-scale supply also sell smaller-scale liquefaction equipment. Small-scale liquefaction can be fed with gaseous hydrogen from bottles, tube trailer deliveries, or they can consume locally produced hydrogen gas (such as through an electrolyser). A typical small-scale liquefier in the region of 30 kg/day will cost approximately £2m and an electrolyser to feed it in the order of £1m. If these sites are planned with sufficient LH2 tank storage onsite they can take bulk deliveries and use the onsite liquefiers to re-liquefy boil off gas which removes the need for LN2. Longer term this type of capability can be utilised for recirculation for endurance type testing.

The CAPEX requirements set out above can be onerous for smaller institutions such as universities or SMEs. Furthermore, a knowledge of LH2 design and handling is required to enable such a facility to be built and operated safely including management of the known inefficiencies and reliability issues if liquefaction equipment is not used consistently.

Examples of onsite liquefaction and testing includes IAAPS, near Bath, who have small-scale green hydrogen production, and are in the process of developing a liquefaction and storage facility. Oxford University is also developing small-scale LH2 storage and use for fundamental research.

Onsite liquefaction has been successfully demonstrated by Element at Kemble Airfield. Element purchases bottled hydrogen gas in multi cylinder pallets (MCP) and liquefies onsite when required. The facility can liquefy up to 12 kg per day which is stored in a vacuum insulated dewar with a zero boil-off system which cycles on and off as needed to remove heat and prevent any boil off of H2 through the vent. This zero-boil off system has been proven to be extremely useful when tests have either failed or taken longer to run or commission than expected meaning the LH2 has had to be stored for several weeks. Another benefit of having an onsite liquefier is that it could also enable recapture H2 vented from the system, reducing operational cost and improving the environmental footprint of the testing. The biggest cost involved in this process is the cost of the gas delivered in MCPs, currently around £100/kg to £200/kg. The key driver for the cost of the bottled hydrogen is the method of delivery and bottle rental which is dependent on the timing of ordering the bottles of gaseous H2.

4.4. H2 Supply Cost Comparison v Scale

Figure 8 is an illustrative analysis comparing the cost per kg of LH2 delivered by the different methods currently available. The analysis assumes for comparison that facilities are at high utilisation and without operational costs as these can vary. The key assumptions used in this analysis are captured in Appendix 1. Each of the methods which require a large upfront capital expenditure typically start out as extremely expensive per kg of LH2. It is difficult to predict the offtake to enable amortisation of this capex over the life of the equipment. Therefore, for comparison these scenarios have been plotted with and without the capital expenditure. This highlights the opportunity if the capex could be funded, as offtake immediately becomes far more affordable for all end users regardless of scale. If these facilities were made available to UK users, the benefit would be felt immediately across UK academia and industry. As costs become more competitive, it is likely to attract overseas customers which could be charged at a different rate to help recoup some of the capex and be reinvested into continuously improving the capabilities.

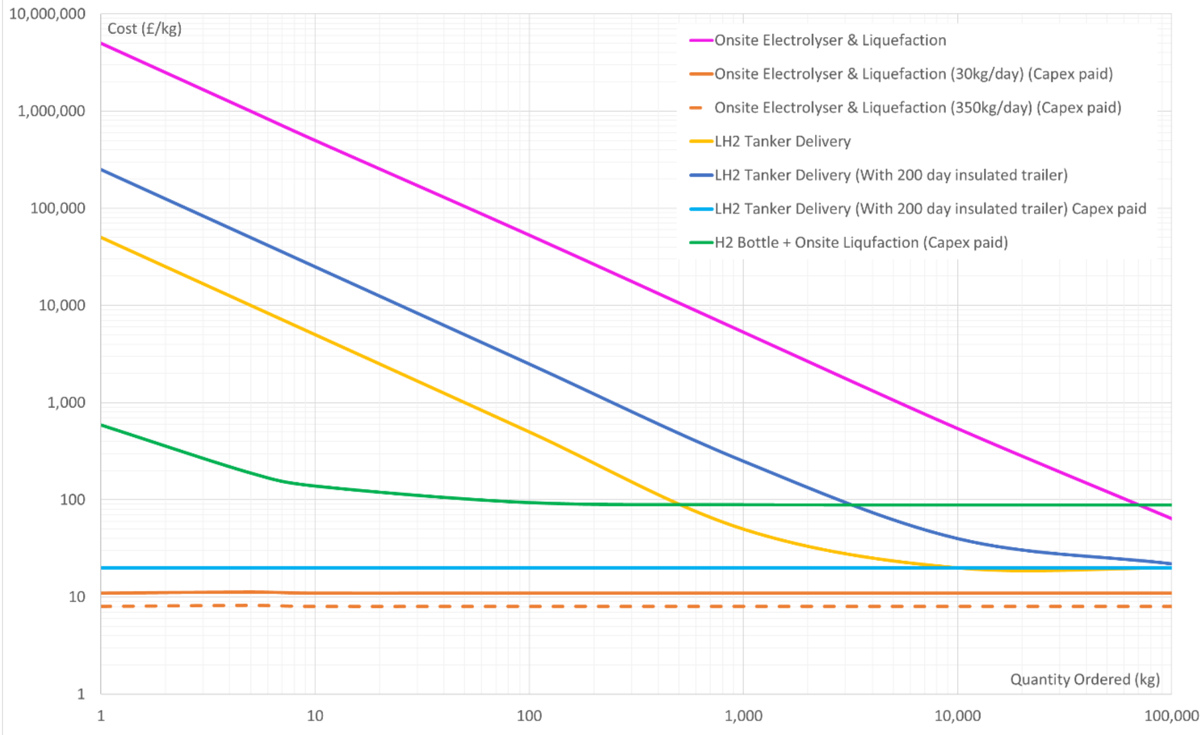

FIGURE 8: LH2 COST VS METHOD OF DELIVERY

If an onsite liquefaction facility has an electrolyser delivering gas to it or the ability to recapture vented H2 and reliquefy, the cost would be closer to the orange line on Figure 8. Costs in the order of £10/kg and the ability to buy LH2 in low volumes would make this globally competitive and attract innovators from around the world. These costings have been based on a small-scale industry standard liquefier similar to that currently owned by Element at its Kemble site. If a larger liquefier with a daily capacity of 350kg/day was commissioned the price would reduce below £10/kg to around £8/kg excluding operating costs, see orange dotted line on Figure 8.

5. Summary

This report on Cryogenic Hydrogen Future Test Infrastructure assesses the readiness of the UK ecosystem to support testing in the development of LH2 aircraft technologies. This forms part of the HCN findings which emphasise the importance of strategic investment in technology, regulation and infrastructure to protect and grow the UK's market share in aerospace.

Key challenges for LH2 testing include the lack of fundamental understanding and experimental data, high costs associated with LH2 testing, and the need for safe test design and operation. The report underscores the necessity of developing a robust LH2 supply network to address existing issues such as high costs and limited availability. It also stresses the importance of establishing comprehensive safety protocols and regulatory frameworks to mitigate risks and ensure efficient operations.

A coordinated approach is required for facility development to avoid duplication and optimise UK investments, to address the requirements from small-scale academic testing to large-scale system testing infrastructure. In the early years of LH2 testing, when knowledge of hazards are immature and skilled operators are few, consolidation of testing to fewer locations is also beneficial. Collaboration across sectors, such as aviation, transport, and marine will strengthen the economic viability of LH2 infrastructure. Enhanced safety standards, training, and regulatory support are essential to building a resilient and competitive LH2 sector in the UK, where no existing space sector and LH2 capability exists.

For small-scale testing that requires up to 1000kg of LH2, an affordable supply is critical. This cost barrier currently limits access for smaller companies and universities, slowing innovation in low Technology Readiness Level (TRL) hydrogen technologies. By addressing this, the UK could become an attractive location for international testing, creating a potential revenue stream and positioning itself as a global hub for LH2 innovation.

A hybrid site is likely the most flexible and cost-effective solution, and such a facility should include:

- A small-scale electrolyser and liquefier to produce small quantities of LH2.
- The ability to reliquefy boil-off gas and capture vented hydrogen from tests.
- A large insulated LH2 storage capacity (at least 2,500 kg) to enable buffering of the small-scale liquefaction production and accept tanker deliveries for high-demand scenarios.

Long Term Strategy and Funding

The successful growth of the UK's LH2 sector requires a clear long-term strategy and sustained funding particularly during early development, when demand uncertainty is highest. Lowering the cost of testing will help academic and industrial players scale more effectively, moving the sector toward self-sufficiency.

Key strategic priorities include:

- Continued monitoring and refinement of the UK's total LH2 demand curve, supporting investment and long-term business cases.
- A coordinated approach to facility development to avoid duplication and maximise value and safety.
- Inclusion of cross-sector demand from marine, transport, energy, and gaseous hydrogen users to strengthen economic viability and improve return on investment.

UK Infrastructure

Infrastructure requires a strategic long-term vision for UK LH2 testing catering to evolving industry needs across the next decade and beyond, investing in a range of test facilities. These should accommodate:

- Small-scale academic testing, supporting R&D and early-stage innovation.
- Large-scale system and endurance testing, which demand substantial LH2 supply and robust infrastructure.
- The model for wind tunnel testing of centralised larger facilities, could be considered for LH2 test facilities. These wind tunnels received support for their development.

UK LH2 Supply

A robust and resilient LH2 supply network is essential, this includes:

- Exploring and supporting all viable domestic supply options, including liquefaction and the development of a UK-based splitter facility.
- Promoting collaboration among end users, particularly smaller test sites, to consolidate deliveries and reduce costs.
- Encouraging joint efforts with LH2 suppliers to improve efficiency, reliability, and cost-effectiveness of UK supply chains.

Safety, Regulations, Standards and Guidance

Enhanced safety protocols and regulatory frameworks are vital to de-risk the adoption of LH2 technologies. Key actions include:

- Developing standardised physical interfaces to allow interoperability between facilities and suppliers.
- Establishing training standards and qualifications to grow the user base and reduce dependency on suppliers.
- Until clear guidance and standards are implemented, a dedicated regulatory point of contact to advise the community should be appointed. This point of contact would assist local authorities with planning approvals to reduce the lead times, guide new users through setup and operational safety and facilitate community feedback to evolve best practices and shape national standards.
- Centralised funding for the development of liquid hydrogen standards to encourage industry collaboration and align on relevant guidelines. Developing standards requires careful consideration and consensus among industry experts.

Collaboration, Coordination and Dissemination

Continued work to convene the sector is important to:

- Ensure safety and build a safety focused culture.
- Build expertise and knowledge, share learnings, guidance and data through a community of practice / forum.
- Build a consolidated demand picture for LH2 across the whole of the UK a to make the business case for LH2 facilities and UK production more robust.

Appendix - Assumptions used in Figure 8

Assumption	Value	Units
Electricity Cost	0.10	£/kWh
Onsite Liquefaction energy (30kg/day)	60	kWh/kg
Onsite Liquefaction energy (350kg/day)	30	kWh/kg
Onsite liquefaction cost	6	£/kg
Electrolyser energy	50	kWh/kg
H2 in and MCP	9.1	kg
MCP cost	750	£
MCP delivery	250	£
MCP rental	250	£/month
Cost of one trailer of 2,500kg of LH2	50,000	£/2,500kg
Cost of LN2 Insulated trailer for 200 days	200,000	£
Mass on one trailer	2,500	kg
Capex Liquefier (30kg/day)	2,000,000	£
Capex Electrolyser (30kg/day)	1,000,000	£
Capex LN2 Insulated Trailer	1,600,000	£
Capex Additional LH2 storage tank	300,000	£

Excludes operating costs such as resource, maintenance, facility upkeep and consumables, as these will vary by site and organisation.

Assumes high utilisation so that fixed overhead costs are recovered by each test campaign.